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Electronic Throttle Valve Takagi-Sugeno Fuzzy Control Based on Nonlinear Unknown Input Observers

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Abstract: This paper deals with the synthesis of a new fuzzy controller applied to Electronic Throttle Valve (ETV) affected by an unknown input in order to enhance the rapidity and accuracy of trajectory tracking performance. Firstly, the Takagi-Sugeno (T-S) fuzzy model is employed to approximate this nonlinear system. Secondly, a novel Nonlinear Unknown Input Observer (NUIO)-based controller is designed by the use of the concept of Parallel Distributed Compensation (PDC). Then, based on Lyapunov method, asymptotic stability conditions of the error dynamics are given by solving Linear Matrix Inequalities (LMIs). Finally, the effectiveness of the proposed control strategy in terms of tracking trajectory and in the presence of perturbations is verified in comparison with a control strategy based on Unknown Input Observers (UIO) of the ETV described by a switched system for Pulse-Width-Modulated (PWM) reference signal.
Keywords: electronic throttle valve, switched system, Takagi-Sugeno fuzzy model, nonlinear unknown input observer, Lyapunov method.

1 Introduction

For further improvement of drivability, fuel economic system and emission performance of vehicles, the Electronic Throttle Control (ETC) systems is required to possess fast transient responses without overshoot and high static precision. Hence, obtaining a proper controller with the ability achieving the requirements is a very interesting topic for the ETC system. The challenging issue is that the control performance of the ETC system is adversely affected by the uncertain system physical parameters related to friction, return spring and gear backlash. To solve the parameter uncertainty problem in the controller design of the ETC system, a lot of efforts have been made from two aspects.

On the one hand, a linear model of the system has been used in several existing control design. In [10] and [23], a nonlinear control strategy has been proposed, consisting of a PID controller and a feedback compensator for friction and limp-home effects. A discrete-time sliding mode controller and observer are designed to realize robust tracking control of the valve system in [7] and [10]. In [20], the variable structure concept is used after the use of feedback backstepping techniques in the intermediate stages of ETV design. In [31], [13], [15] and [21], the emphasis is on the development of an adaptive control strategy, which is aimed to enhance the control strategy robustness with respect to process parameter variations, caused by production deviations and variations of external conditions. In [14] and [18], a PID-type fuzzy logic controller has been proposed. In [16], fault tolerant control has been proposed for the ETV described by a switched discrete-time systems with input disturbances and actuator faults. In [6], the Smith-predictor control has been adapted for controlling the electronic throttle body over a delay-driven network.

On the other hand, among nonlinear control theory, the Takagi-Sugeno (T-S) fuzzy system [36] has been the most active branch of the fuzzy control field, [19], [20], [12], [39] and [13]. The stability and stabilisation of T-S systems has been the subject of many works either in the continuous case or in the discrete one, [2] and [3]. The Parallel Distribution Compensation (PDC) technology has been widely employed to design the fuzzy controller for T-S fuzzy systems in [26] and [28]. The problem of robust tracking control is investigated for a class of nonlinear systems approximated by a fuzzy T-S model in [11]. In [32], a fuzzy H_2 guaranteed cost sampled-data control problem for nonlinear time-varying delay systems is studied. An observer can be used for state estimation when the system states are unmeasurable [27]. The observer-based state feedback PDC controller can be employed to settle the unmeasured state condition as shown in [18] and [40]. In [19], an adaptive observer in the unknown input estimation form is proposed for a system with unmeasured premise variable. In [25], an adaptive observer is designed for the estimation of unmodeled dynamics in a T-S system. In [9], a T-S observer with parameter estimation was designed for a heat exchanger fouling detection problem. In [5], a joint state and parameter estimation observer was proposed for T-S systems whose matrices depend on unknown parameters. In [22], Nonlinear Unknown Input Fuzzy Observer (UIFO) has been used for fuzzy T-S systems to design the fuzzy fault tolerant control. In [7], an approach for Nonlinear Unknown Input Observer (NUIO) design for nonlinear systems has been proposed.

In this paper, a new control strategy based on NUIO is proposed for the ETV described by T-S fuzzy systems. NUIO is used to estimate the position of an automotive throttle valve. Then, an estimated-state feedback control law is developed via PDC. Based on Lyapunov method, asymptotic stability conditions of the error dynamics is given in LMIs to design the observer parameters. The proposed control strategy is then investigated and compared to switching control based on Unknown Input Observer (UIO). The following part of this article is organized as follows: In Section II, the topology of the ETV is presented and modeled. The proposed control strategy is explained and detailed in section III. Section IV is devoted to comparison and discussions, and finally, section VI ends the paper with a conclusion.

2 Electronic throttle valve topology

The studied electronic throttle control system includes an accelerator pedal, an Electronic Control Unit (ECU) and a throttle body, shown in figure 1.

The throttle body is composed of a DC motor, a reduction gear set, a valve plate, a position sensor and two nonlinear return springs [21].

The control signal, provided by the ECU, is the armature voltage of a DC-motor which is controlled by changing the PWM duty cycle. It generates the rotational torque to regulate the throttle plate position. Nomenclature used in the model is presented in the appendix A.

2.1 State space representation

The electrical part of the throttle body is modeled by (1) and the electromechanical part by (2).

$$u = L\dot{i} + Ri + e \tag{1}$$

$$e = K_v\dot{\theta}_m \tag{2}$$

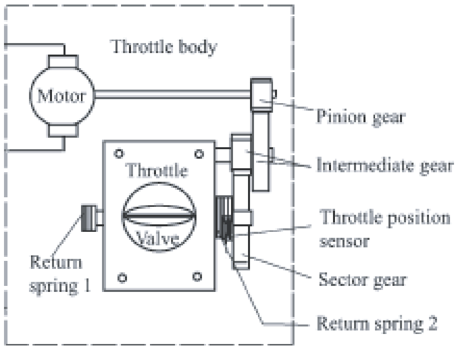

Figure 1: The electronic throttle body

$u(t)$ is the voltage, $i(t)$ the armature current and e the electromotive force, [24].
The electrical torque C_e is considered, in this study, such that

$$C_e = K_t i \tag{3}$$

By considering the stick-slip friction torque $T_f(\omega)$ and the nonlinear spring torque $T_{sp}(\theta)$, the mechanical part of the throttle body is modeled by (4), [24].

$$J_{tot}\dot{\omega} = -B_{tot}\omega - T_f(\omega) - T_{sp}(\theta) + C_e \tag{4}$$

There are many types of friction involved in the motion of throttle plate such as Coulomb, viscous, stribeck, rising static frictions and presliding displacement [20]. In this paper, the Coulomb friction model $T_f(\omega)$ is considered given by

$$T_f(\omega) = F_s \operatorname{sgn}(\omega) \tag{5}$$

where F_s is a positive constant parameter.
The typical feature of the ETV includes a stiff spring, used as a fail-safe mechanism, which forces the valve plate to return to the position slightly above the closed position when no power is applied. Moreover, the motion of the valve plate is limited between θ_{max} and θ_{min} angles. These limitations are realized by a highly stiff spring, ideally with infinite gain. The nonlinear spring expression is written such as

$$T_{sp}(\theta) = m_1(\theta - \theta_0) + D \operatorname{sgn}(\theta - \theta_0) \tag{6}$$

The gear ratio γ is given by (7).

$$\gamma = \frac{\theta_m}{\theta} = \frac{1}{K_{g1}K_{g2}} \tag{7}$$

such that: $K_{g1} = N_p/N_{\text{int}\,l}$ and $K_{g2} = N_{\text{int}\,s}/N_{\sec t}$.

From equations (1), (2), (3) and (7) and by subtituting the expressions $T_{sp}(\theta)$ and $T_f(\omega)$ into (4), it comes the following ETV model

$$\begin{cases} \dot{\theta} = K_{g1}K_{g2}\omega \\ \dot{\omega} = -\frac{m_1}{J_{tot}}(\theta - \theta_0) - \frac{D}{J_{tot}} \operatorname{sgn}(\theta - \theta_0) - \frac{B_{tot}}{J_{tot}}\omega - \frac{F_s}{J_{tot}} \operatorname{sgn}(\omega) + \frac{K_t}{J_{tot}} i \\ L\dot{i} = -K_v\omega - Ri + u \end{cases} \tag{8}$$

2.2 System identification

By substituting C_e, T_f and T_{sp} into (4) and by neglecting the torque generated by the airflow C_a, the two nonlinearities $\mathrm{sgn}(\theta-\theta_0)$ and $\mathrm{sgn}(\omega)$ and the constant $\frac{m_1}{J_{tot}}\theta_0$, the ETV can be modelized by the following transfer function $H(s)$ [37].

$$H(s) = \frac{\theta(s)}{u(s)} = \frac{(180/\pi)K_e/\gamma}{LJ_{tot}s^3 + (RJ_{tot} + LB_{tot})s^2 + (RB_{tot} + K_vK_e + K_sL)s + K_sR} \tag{9}$$

with: $K_s = (180/\pi/\gamma)m_1$ and s the Laplace operator.

From equation (9), the ETV can be modelized by two linear models identified from the default position of the throttle plate for two values of the parameter K_s, [37]: a model representing the position of the plate above the position by default and the other the position of the plate below the position by default.

Switching between these two models of the ETV is equivalent to enabling and disabling the current model. Changing model and process structure raise problems such as detection model switching and maintain model tracking. Moreover, it is essential to consider the nonlinearities in the modeling phase, so that the behavior of the real system is described over a wide range of operation. It is, therefore, possible to consider modeling based on the concept of fuzzy logic. Indeed, in this case, a novel Takagi-Sugeno fuzzy model of the ETV is proposed which uses a base of locally linearised models.

2.3 T-S Fuzzy modeling

A reduced model of the ETV is firstly provided. To simplify the analysis, the motor armature inductance L will be assumed negligible then (1) and (2) can be rewritten as

$$-K_v\omega - Ri + u = 0 \tag{10}$$

Let $x(t) = [x_1(t)\ x_2(t)]^T$ and $x_{10} = \theta_0$, with

$$x_1 = \theta,\ x_2 = K_{g1}K_{g2}\omega \tag{11}$$

By substituting the value of i in the throttle valve dynamical system (8), the state space form can be simplified as

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_{21}(x_1 - x_{10}) - \lambda\,\mathrm{sgn}(x_1 - x_{10}) + (a_{22} - a_{23}\frac{a_{32}}{a_{33}})x_2 - \mu\,\mathrm{sgn}(x_2) - \frac{a_{23}}{a_{33}}u \end{cases} \tag{12}$$

where the coefficients of the ETV model according to the physical parameters are given by: $a_{21} = m_1K_{g1}K_{g2}/J_{tot}$, $a_{22} = -B_{tot}/J_{tot}$, $a_{23} = K_tK_{g1}K_{g2}/J_{tot}$, $a_{32} = -K_v/K_{g1}K_{g2}$, $a_{33} = -R$, $\mu = F_sK_{g1}K_{g2}/J_{tot}$ and $\lambda := DK_{g1}K_{g2}/J_{tot}$.

The number of the local models depends on the nonlinear system complexity and the choice of the activation functions structure [1]. The polytope is obtained with $N = 2^r$ peaks where r is the number of premise variables considered for: $r = 2$.
Then, the ETV system can be transferred as the following T-S models.

$$Rule1: \ IF\ x_1(t) < x_{10}\ AND\ x_2(t) < 0\ THEN \\ \begin{cases} \dot{x}(t) = A_1x(t) + B_1u(t) + D_1d(t) \\ y(t) = C_1x(t) \end{cases} \tag{13}$$

$$Rule2: \; IF \; x_1(t) > \; x_{10} \; AND \; x_2(t) < \; 0 \; THEN$$
$$\begin{cases} \dot{x}(t) = A_2x(t) + B_2u(t) + D_2d(t) \\ y(t) = C_2x(t) \end{cases} \tag{14}$$

$$Rule3: \; IF \; x_1(t) < \; x_{10} \; AND \; x_2(t) > \; 0 \; THEN$$
$$\begin{cases} \dot{x}(t) = A_3x(t) + B_3u(t) + D_3d(t) \\ y(t) = C_3x(t) \end{cases} \tag{15}$$

$$Rule4: \; IF \; x_1(t) > \; x_{10} \; AND \; x_2(t) > \; 0 \; THEN$$
$$\begin{cases} \dot{x}(t) = A_4x(t) + B_4u(t) + D_4d(t) \\ y(t) = C_4x(t) \end{cases} \tag{16}$$

with

$$A_1 = \begin{pmatrix} 0 & 1 \\ a_{21} + \lambda & a_{22} - a_{23}\frac{a_{32}}{a_{33}} + \mu \end{pmatrix}, \; A_2 = \begin{pmatrix} 0 & 1 \\ a_{21} - \lambda & a_{22} - a_{23}\frac{a_{32}}{a_{33}} + \mu \end{pmatrix}$$

$$A_3 = \begin{pmatrix} 0 & 1 \\ a_{21} + \lambda & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \mu \end{pmatrix}, \; A_4 = \begin{pmatrix} 0 & 1 \\ a_{21} - \lambda & a_{22} - a_{23}\frac{a_{32}}{a_{33}} - \mu \end{pmatrix}$$

$$B_1 = B_2 = B_3 = B_4 = \begin{pmatrix} 0 \\ -\frac{a_{23}}{a_{33}} \end{pmatrix}$$

$$C_1 = C_2 = C_3 = C_4 = \begin{pmatrix} 1 & 0 \end{pmatrix}$$

$$D_1 = D_2 = D_3 = D_4 = 1e3. \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

The global fuzzy Takagi-Sugeno model is given, for $i \in \xi = \{1, ..., 4\}$, as follows

$$\begin{cases} \dot{x}(t) = \sum\limits_{i=1}^{4} h_i(z(t))(A_ix(t) + B_iu(t) + D_id(t)) \\ y(t) = \sum\limits_{i=1}^{4} h_i(z(t))C_ix(t) \end{cases}, \; i \in \xi \tag{17}$$

with

$$h_i(z(t)) = \frac{w_i(z(t))}{\sum\limits_{i=1}^{4} w_i(z(t))}, \; w_i(z(t)) = \prod_{j=1}^{2} M_j^i(z_j(t)) \tag{18}$$

M_j^i is the j^{th} fuzzy set of the i^{th} rule, $z_1(t), z_2(t)$ are the known premises variables and $M_j^i(z_j(t))$ the membership value of $z_j(t)$ in M_j^i.
Therefore, from (18) the following properties are satisfied

$$\sum_{i=1}^{4} h_i(z(t)) = 1, \; h_i(z(t)) \geqslant 0 \; \forall i \in \xi \tag{19}$$

The ETV control law should be designed to guarantee the tracking of the throttle movement θ for a desired reference signal with satisfactory transient performance and steady-state position error as well as robustness to nonlinearity parameter variations of friction, nonlinear spring and external disturbance.

3 Proposed T-S fuzzy control strategy

3.1 Structure of the proposed T-S fuzzy control strategy

For the T-S fuzzy model (17), the following control law based on the estimated state is proposed, as shown in figure 2.

$$u_{TS}(t) = -\sum_{i=1}^{N} h_i(z(t))(K_{TS,i}\hat{x}(t) + y^d(t)) \tag{20}$$

The main contribution of this article is to design an estimated feedback control law for the ETV described by T-S fuzzy model. A Nonlinear Unknown Input Observer (NUIO) is used to estimate the system state $\hat{x}(t)$. The control should maintain the system output closed to the desired trajectory $y^d(t)$ even in the presence of unknown input $d(t)$. A supervisor is implemented to calculate the weighting functions $h_i(z(t))$. The design of the fuzzy controller shares the same fuzzy sets as the fuzzy model and the same weights.

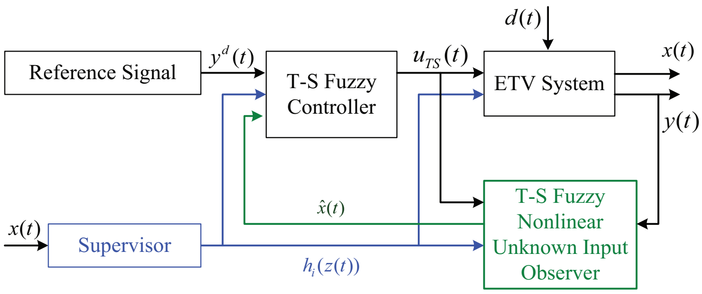

Figure 2: Proposed T-S Fuzzy controller structure for the ETV

$K_{TS,i} \in \mathbb{R}^{p\times n}$, $i \in \xi$, is the i^{th} feedback gain vector and $y^d(t) \in \mathbb{R}^p$ the reference input.
The purpose of the next sub-section is to design an estimated state-feedback control defined via PDC ensuring the stability of the closed-loop system.

3.2 Parallel distributed compensation

The design of the PDC fuzzy controller shares the same fuzzy sets as the fuzzy model and the same weights $w_i(z(t))$ in the premise parts [34]. The state feedback fuzzy controller is constructed via PDC as follows [35]

$$\begin{array}{c}\text{IF } z_1(t) \text{ is } M_1^i \text{ AND...AND } z_r(t) \text{ is } M_r^i \\ \text{THEN } u(t) = -\sum\limits_{i=1}^{N} h_i(z(t))K_{TS,i}x(t)\end{array} \tag{21}$$

The design of the fuzzy regulator is to determine the local feedback gains $K_{TS,i} \in \mathbb{R}^{p\times n}$.
By substituting (21) into (17), the closed loop model is written as

$$\begin{cases} \dot{x}(t) = \sum\limits_{i=1}^{N}\sum\limits_{i=j}^{N} h_i(z(t))h_j(z(t))Q_i x(t) \\ y(t) = \sum\limits_{i=1}^{N} h_i(z(t))C_i x(t) \end{cases} \tag{22}$$

with: $Q_i = (A_i - B_i K_{TS,i})$.
Stability conditions for ensuring stability of (17) is derived using Lyapunov approach for linear continuous systems.

Theorem 1. *The equilibrium of the continuous fuzzy system described by (17) is asymptotically stable in the large if there exists a common positive definite matrix* $X1$ *such that, [34]*

$$A_i^T X1 + X1 A_i < 0 \tag{23}$$

for $i \in \xi$*; that is, for all the subsystems.*

By applying theorem 1 to (22), we can derive stability conditions.

Theorem 2. *The equilibrium of the continuous fuzzy control system described by (22) is asymptotically stable in the large if there exists a common positive definite matrix* $X1$ *such that, [34]*

$$Q_{ii}^T X1 + X1 Q_{ii} < 0 \tag{24}$$

$$\left(\frac{Q_{ij}+Q_{ji}}{2}\right)^T X1 + X1\left(\frac{Q_{ij}+Q_{ji}}{2}\right) \leqslant 0 \;\; i<j \tag{25}$$

for all i *and* j *excepting the pairs* (i,j) *such that* $h_i(z(t))h_j(z(t)) = 0,\ \forall t$.

The stability conditions of theorems 1 and 2 can be expressed as LMIs, [35].
By using: $X = X1^{-1}$ and: $M_i = K_{TS,i}X$, the satisfaction of LMIs conditions needs to find $X > 0$ and M_i such that, $\forall i \in \{1, ..., N\}$,

$$XA_i^T + A_i X - B_i M_i - M_i^T B_i^T < 0 \tag{26}$$

$$X(A_i^T + A_j^T) + (A_i + A_j)X - (B_i M_j + B_j M_i) - (B_i M_j + B_j M_i)^T < 0 \tag{27}$$

In practice, all states are not fully measurable; then, a nonlinear unknown input observer for T-S fuzzy models is proposed in order to implement the estimated state-feedback controller. The concept of PDC is employed to design the following NUIO structure in the next part.

3.3 NUIO design and stability analysis

The concept of PDC is employed to design NUIO for the T-S fuzzy model (17). The i^{th} observer rule is of the following form, [7]

$$\begin{array}{c}\text{IF } z_1(t) \text{ is } M_1^i \text{ AND...AND } z_r(t) \text{ is } M_r^i \\ \text{THEN } \dot{v}(t) = A_i v(t) + G_i u(t) + L_i y(t),\ i \in \xi\end{array} \tag{28}$$

The overall fuzzy observer is given as

$$\begin{cases} \dot{v}(t) = \sum\limits_{i=1}^{N} h_i(z(t))(N_i v(t) + G_i u(t) + L_i y(t)) \\ \qquad \hat{x}(t) = v(t) - Ey(t) \end{cases},\ i \in \xi \tag{29}$$

where N_i, G_i and L_i, $i \in \xi$ and E are unknown matrices to be designed, [7].
Let's define the error $e(t) = \hat{x}(t) - x(t)$, it follows from (17) and (29) that

$$\begin{aligned}\dot{e}(t) = &\sum_{i=1}^{N} h_i(z(t))N_i e(t)\\ &+\sum_{i=1}^{N} h_i(z(t))\{N_i + K_iC_i - (I + EC_i)A_i\}x(t)\\ &+\sum_{i=1}^{N} h_i(z(t))\{G_i - (I + EC_i)B_i\}u(t)\\ &-\sum_{i=1}^{N} h_i(z(t))(I + EC_i)D_i d(t)\end{aligned} \tag{30}$$

with

$$K_i = L_i + N_i E \tag{31}$$

A sufficient condition, for the observer given by (29) to be an NUIO, is given as in the following theorem.

Theorem 3. *For the observer given by (29), if K_i, $i \in \xi$ and E are chosen such that*

$$\begin{array}{c} N_i = (I + EC_i)A_i - K_iC_i \\ G_i = (I + EC_i)B_i \\ L_i = K_i - N_i E \\ EC_iD_i = -D_i \end{array} \tag{32}$$

and if a positive definite symmetric matrix $X2$ can be found to satisfy the following inequalities

$$N_i^T X2 + X2 N_i < 0,\ \ i \in \xi \tag{33}$$

then the error dynamics given by (30) is asymptotically stable at the origin. Hence the observer given by (29) is an NUIO, that is, $e(t)$ goes to zero asymptotically and is invariant with respect to the unknown inputs $d(t)$, [7].

Proof. The proof is given in the appendix B.

Theorem 4. *For the observer given by (29), if there exist matrices $\bar{K}_i$, $i \in \xi$, a matrix $\bar{Y}$ and a positive definite symmetric matrix X such that the following LMIs are satisfied*

$$\begin{array}{c} [(I + UC_i)A_i]^T X2 + X(I + UC_i)A_i \\ +(VC_iA_i)^T\bar{Y}^T + \bar{Y}(VC_iA_i) - C_i^T\bar{K}_i^T - \bar{K}_iC_i < 0 \end{array} \tag{34}$$

with: $U = -D_i(C_iD_{T1})^+$ and: $V = I - C_iD_{T1}(C_iD_{T1})^+$; then by letting $K_i = X2^{-1}\bar{K}_i$ and $Y = X2^{-1}\bar{Y}$ and computing the observer gains using (39) and (32), the error dynamics given by (30) is asymptotically stable at the origin. Hence, the observer given by (29) is a NUIO, that is, $e(t)$ goes to zero asymptotically and is invariant with respect to the unknown inputs $d(t)$, [7].

Proof. The proof is given in the appendix C.

In the next section, in order to evaluate the proposed control laws performance against the nonlinearities such as friction and limp home spring of ETV, the position is examined for a PWM signal.

4 Results and discussion

In order to test the position of the ETV for a PWM reference signal provided by the T-S fuzzy control, a comparative study is performed. The proposed control strategy is then investigated and compared to switching control based on UIO proposed in our previous work, [16] and [17].

To illustrate the effectiveness of the proposed control strategy, a T-S fuzzy model of the ETV, is firstly, provided. The considered model is given by (12) with the state region $0rad < x_1(t) < \pi/2rad$ and $-80rad/s < x_2(t) < 80rad/s$.
The considered ETV system parameters, for the numerical simulations, are presented in table 4, as given in [20].

Table 1: Parameter values for simplified model

Parameters	**Values**
a_{21}	1/18
a_{22}	$-1.6801e3$
a_{23}	-32.9820
a_{32}	-0.0245
a_{33}	-1.0980
μ	$4.7438e2$
λ	$2.1073e3$

Solutions satisfying stability conditions under LMIs of the theorem 2 are found for symmetric definite positive matrix $X1$ given by (35).

$$X1 = \begin{pmatrix} 32.7434 & -8.9104 \\ -8.9104 & 32.7434 \end{pmatrix} \tag{35}$$

Then, the feedback gains are given by

$$K_{TS,1} = \begin{bmatrix} 0.7505 & 0.5061 \end{bmatrix}, \; K_{TS,2} = \begin{bmatrix} 0.7505 & \text{-}0.5716 \end{bmatrix}$$
$$K_{TS,3} = \begin{bmatrix} \text{-}1.6091 & 0.5061 \end{bmatrix}, \; K_{TS,4} = \begin{bmatrix} \text{-}0.5050 & \text{-}0.2716 \end{bmatrix}$$

Solutions satisfying stability conditions under LMIs of the theorem 3 and 4 are found for symmetric definite positive matrix $X2$ given by (36). Then, the rest parameters of NUIO are calculated.

$$X2 = \begin{pmatrix} 0.8820 & 0 \\ 0 & 0.0002 \end{pmatrix} \tag{36}$$

The throttle plate follows a PWM signal of amplitude ranged from 0 to 1.5708 rad and frequency $f = 0.2Hz$ with a white Gaussian noise $d(t)$ given by figure 3.

The system responses obtained from initial conditions: $x_0(t) = [0.1\ 0]^T$ are shown in figures 4-6.

Figure 4 shows the evolution of the throttle plate angle in the presence of unknown input $d(t)$ with the switched system and the T-S fuzzy system. For the switched system, the throttle plate tracks the reference signal with settling time equal to $2.5s$ and fluctuations due to the noise. Whereas for the same reference input and by using the T-S fuzzy system, the throttle plate tracks the reference signal with settling time equal to $0.25s$, rotor angular velocity average value: $\pm 1.0295 rad/s$, figure 7, and ECU output voltage ranging from: $-2.7\ V$ to $1.6\ V$, figure 6.

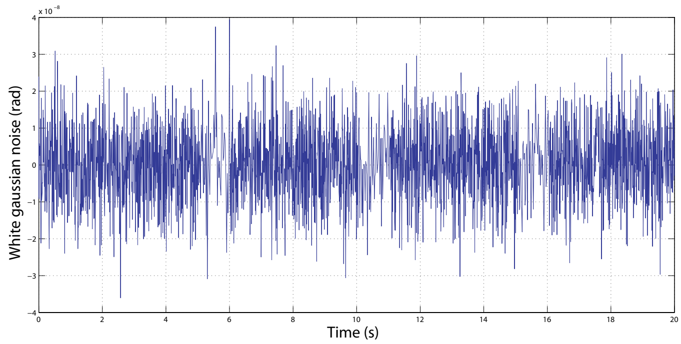

Figure 3: White gaussian noise

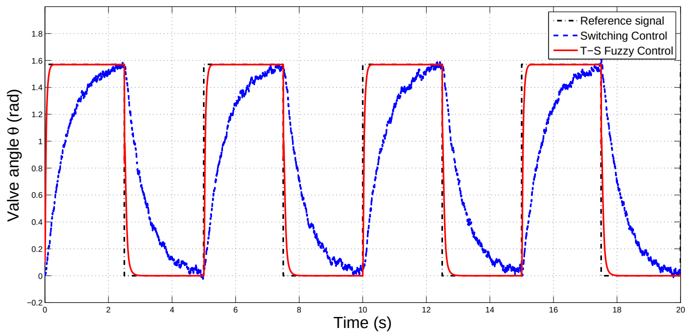

Figure 4: Valve angle position

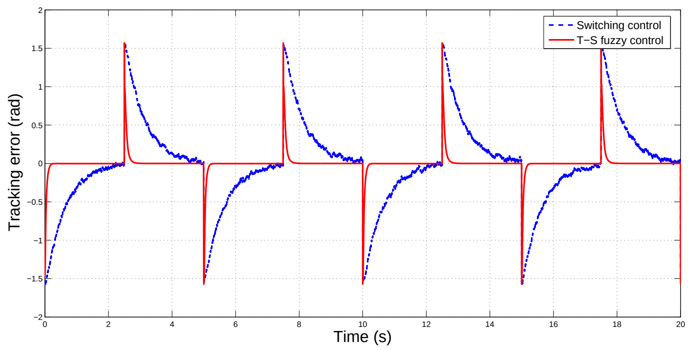

Figure 5: Tracking error

It can be observed, from figure 5, that the error between the throttle plate angle and its steady-state value has been greatly reduced, in terms of average value, to: $\pm 40.10^{-3} rad$ using the proposed strategy against: $\pm 40.10^{-2} rad$ with the switched system technique.

From figure 8, simulation results using the proposed T-S fuzzy control strategy show that the controller yields good tracking performance for a step perturbation amplitude of $0.2rad$ at $t = 6s$ with a small error between the throttle plate angle and its steady state.
From the simulation results, we consider that the performances of the proposed approach for T-S fuzzy system control are satisfactory and allow normal functioning of the system in spite of the fast acceleration and deceleration process even in the presence of an unknown input $d(t)$ and perturbation. Indeed, the electronic throttle control system has a fast transient response

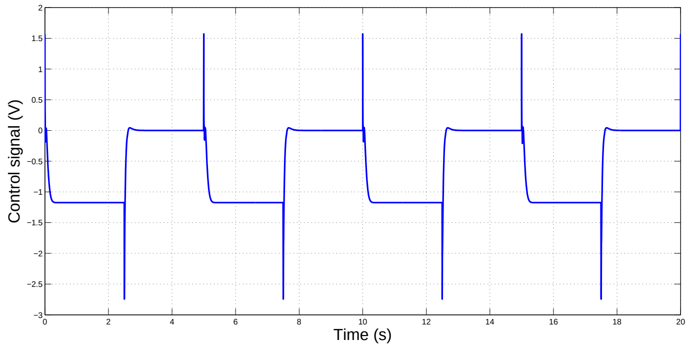

Figure 6: Control signal obtained by T-S fuzzy control

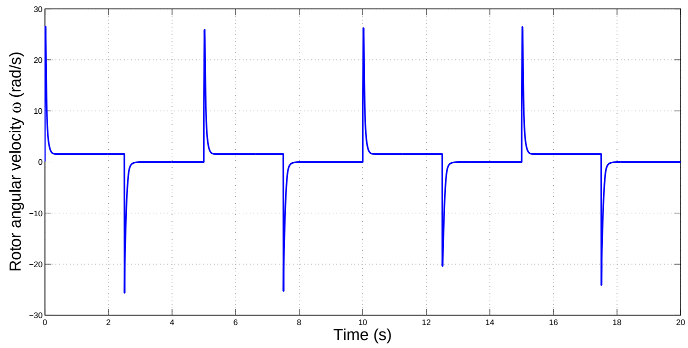

Figure 7: Rotor angular velocity obtained by T-S fuzzy control

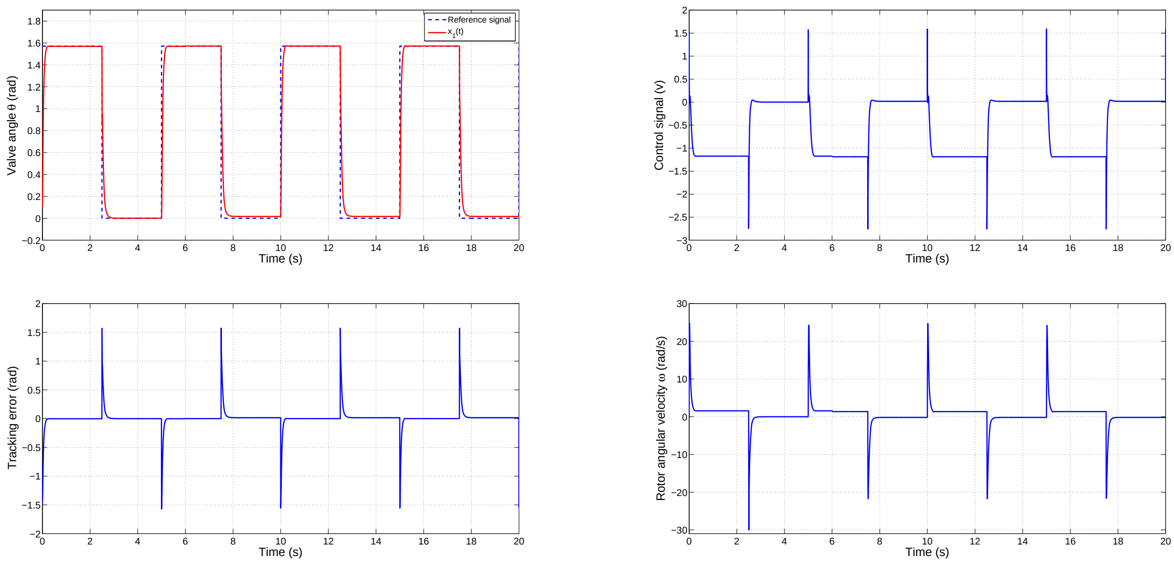

Figure 8: Simulation results with step perturbation

without overshoot and high static precision.
The results of this paper may inspire further research interest. Certainly, actuator and sensor faults occur, a Fault Tolerant Controller (FTC) based on T-S observer strategy would be

designed. It should be noted also that the control strategy would be given from the view of discontinuous systems. Then, experimental validation would be performed to illustrate the performance of the presented throttle control for tracking a reference position.

5 Conclusion

The difficulty in controlling the studied Electronic Throttle Valve (ETV) mainly lies in the nonlinearities related to the friction, the return spring and the gear mechanism. Therefore, a new control strategy based on Nonlinear Unknown Input Observer (NUIO) has been proposed for the ETV. Firstly, a Takagi-Sugeno fuzzy model for the ETV with unknown input has been constructed. Then, NUIO, designed via the Parallel Distributed Compensation (PDC), are used to estimate the unmeasurable system status. Lyapunov theory and Linear Matrix Inequalities (LMIs) have been used for ensuring the stability of the error system. The proposed approach has been achieved in comparison with Unknown Input Observer (UIO)-based control for the ETV described by switched system. UIO is designed and formulated in terms of Lyapunov theory and LMIs technique in order to maintain asymptotic stability. The simulation results have indicated the usefulness of the proposed approach for T-S fuzzy disturbed system control in terms of tracking a desired valve angle position and pertubation rejection with a fast transient response and high static precision for Pulse-Width-Modulated (PWM) reference signal.

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Appendix A. Nomenclature

J_{tot}	Total moment of inertia	$Kg.m^2$
B_{tot}	Total damping constant	$N.m/rad$
N_p	Tooth number of pinion gear	-
$N_{\text{int}\,l}$	Tooth number of large intermediate gear	-
$N_{\text{int}\,s}$	Tooth number of small intermediate gear	-
$N_{\sec t}$	Tooth number of sector gear	-
L	Motor inductance	H
R	Motor resistance	Ω
K_t	Motor torque constant	$N.m/A$
K_v	Motor back EMF constant	$V.s/rad$
θ_0	Spring default position	rad
θ_{min}	Spring min position	rad
θ_{max}	Spring max position	rad
θ	Valve plate position	rad
θ_m	Motor rotational position	rad
ω	Rotor angular velocity	rad/s
D	Spring offset	$N.m$
m_1	Spring gain	$N.m/rad$

Appendix B. Proof of theorem 3

Proof: Using (32), it follows from (30) that

$$\dot{e}(t) = \sum_{i=1}^{N} h_i(z(t)) N_i e(t) \tag{37}$$

Using (36), it is now quite standard to prove the stability property.
It is easy to see that (32) implies that

$$EC_i(D_1, \cdots, D_N) = -(D_1, \cdots, D_N) \tag{38}$$

Assumption: $rank(EC_i(D_1, \cdots, D_N)) = rank((D_1, \cdots, D_N))$.
Under assumption, there exists a nonsingular matrix T_D such that $(D_1, \cdots, D_N)T_D = (D_{T1}\ 0)$, where D_{T1} is of full column rank. This implies that $C_i D_{T1}$ is of full column rank. (38) requires all the possible solutions for E to have the following form

$$E = -D_i(C_i D_{T1})^+ + Y(I - C_i D_{T1}(C_i D_{T1})^+) \tag{39}$$

where Y can be any compatible matrix and $X^+ = (X^T X)^{-1} X^T$.
In order to provide an efficient design method, we reformulate the sufficient conditions given by (32) and (36) as LMIs.

Appendix C. Proof of theorem 4

Proof: Using (39), it is easy to show that LMI based conditions given by (34) are equivalent to those conditions required in the theorem 3. The theorem is therefore proved.